Ferroelectric Liquid Crystal Based Polarization Filters

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Liquid crystal tunable filters (LCTFs) are gaining wide acceptance in such diverse areas as optical fiber communications, astronomy, remote sensing, pollution monitoring, color generation for display and medical diagnostics. LCTFs based on cholesteric LC and nematic LC, using Fabry-Perot and polarization interference effects are currently available from several vendors, including BNS. This paper addresses extension of the principles involved in tuning LCTFs to devices based on ferroelectric-liquid crystals (FLCs).

Background

The large aperture and imaging capability of LCTFs represent a distinct advantage over conventional dispersive spectral analysis techniques. Furthermore, benefits of LCTFs over acousto-optic tunable filters include low power consumption, low addressing voltage, excellent image quality and large clear aperture.

There are two compelling arguments for considering ferroelectric LC-based tunable optical filters over their nematic LC cousins: fast response time and increased field-of-view. Ferroelectric LC elements have tuning speeds in the 30µs-250µs range, depending on the device thickness, the material used, switching voltage and temperature. This is 100 times faster than speeds typically observed in nematic LC mixtures. Unlike nematic LC, the switching mechanism of ferroelectric LC is conducive to acceptance angles that are independent of applied field.

Introduction to Polarization Interference Filters

Both discrete and continuous tunable filters presented subsequently are based on a technique known as polarization interference. In this scheme, the wavelength dependence of polarization induced by multiple-order waveplates is manipulated to produce a wavelength dependent transmission.

Passive Lyot Filters

The structures considered here are based on the work of Lyot and Ohmann. These filters are made up of a cascade of filter units, or stages, requiring two linear polarizers (parallel or crossed) bounding a linear multiple-order retarder oriented at 45°. The filter stage functions as a two-beam (Michelson) interferometer, based on polarization rather than wavefront shearing. The transmission of a single stage, like a Michelson interferometer, is an oscillatory function of the path-length-difference. As shown in Figure 1, the thicker the retarder, the narrower the pass bands. By cascading a series of these filter stages, a bandpass filter can be synthesized. Figure 1 shows the characteristic replicated *sinc* function transmission of a classic Lyot style filter. Note that the spectrum is produced by a geometric relationship (*d, 2d, 4d, 8d)* of retarder thickness in subsequent stages.

Tuning the wavelength of peak transmission in the Lyot polarization interference filter (PIF) requires changing the path-length difference, or retardance, of each filter stage. This is precisely how PIFs are tuned using homogeneously aligned nematic liquid crystal. Application of an electric field in a nematic device produces an analog variable retardation. It is therefore quite obvious how a passive PIF can be retrofitted to be active with nematic LC. Conversely, the electro-optic response of a homogeneously aligned FLC device functions as a fixed retarder with variable orientation. The mechanism for tuning an FLC-based PIF is therefore not obvious.

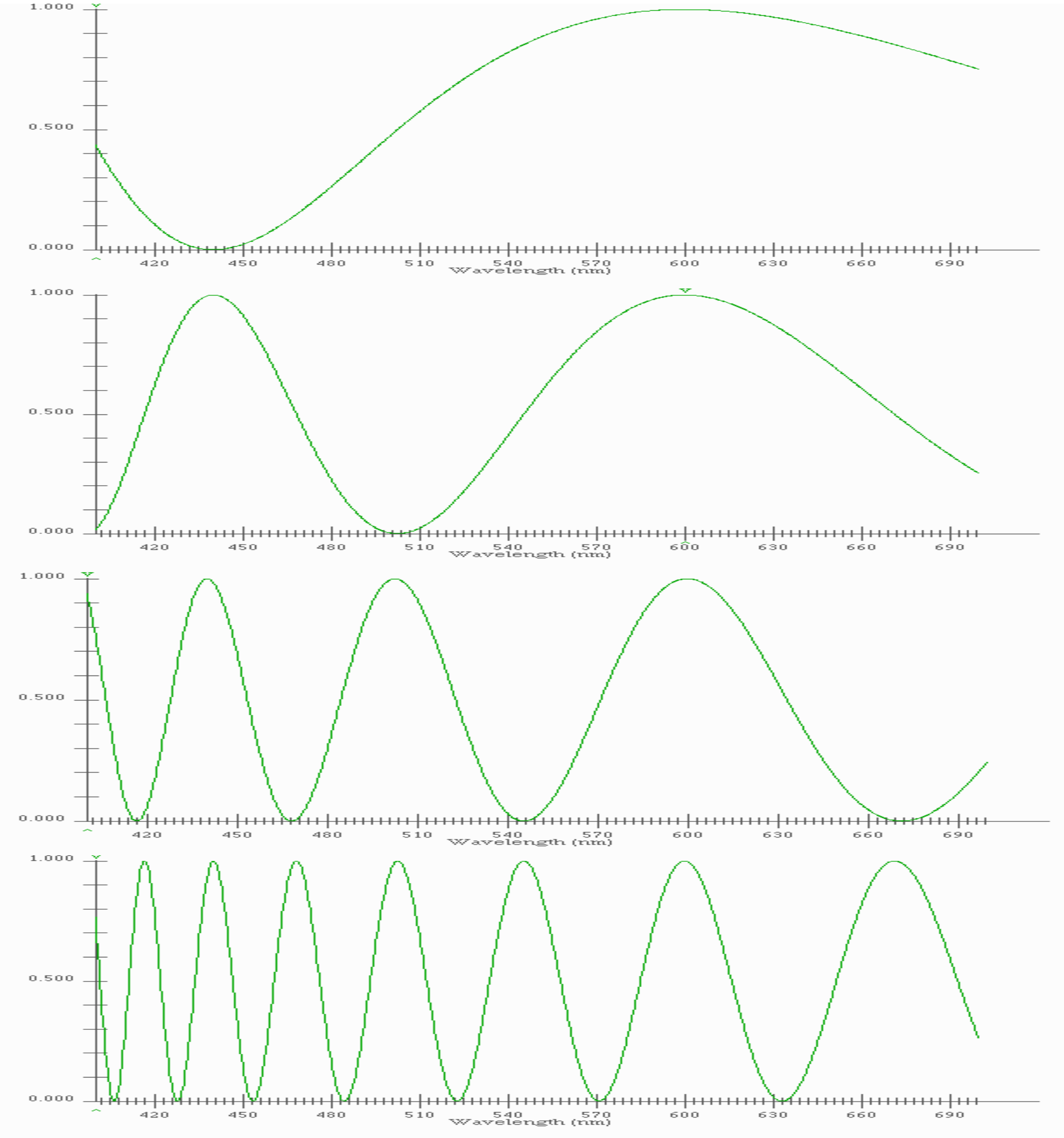

Figure 1 - The transmission spectrum from each stage (d,2d,4d,8d) of a classic four-stage Lyot-Ohmann polarization interference filter (PIF).

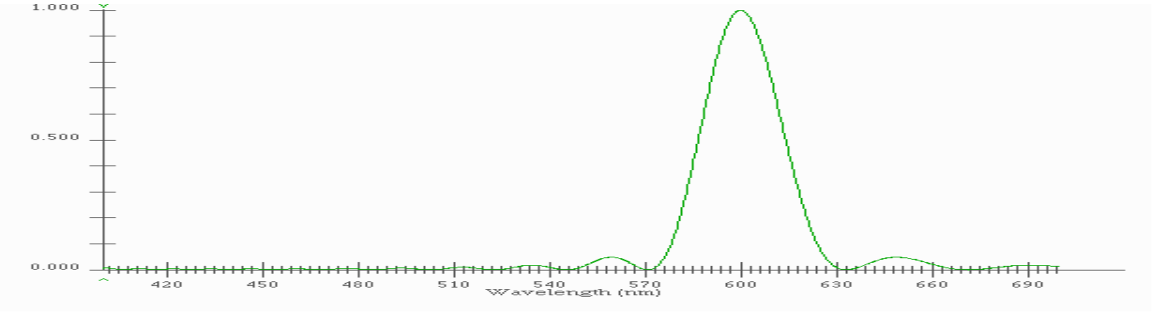

Figure 2 - The characteristic composite transmission spectrum.

Discrete Tuning with FLC

The most obvious use of FLC and a tuning element is as a switchable half waveplate. Lyot and others proved that any desired periodic spectrum can be implemented with a series of passive retarders between a pair of polarizers, just as any mathematical waveform can be produced with a series of sine waves. Simple sinusoidal spectra are easily implemented with a few passive retarders, while more complex spectra (such as square waves with steep transition regions) require more retarders. Regardless of the spectrum generated, the nature of the birefringent filter is to separate desirable light and undesirable light into two orthogonal polarizations. As shown in Figure 2, by following the filter structure with an FLC switch, one can alternate between these two complementary spectra.

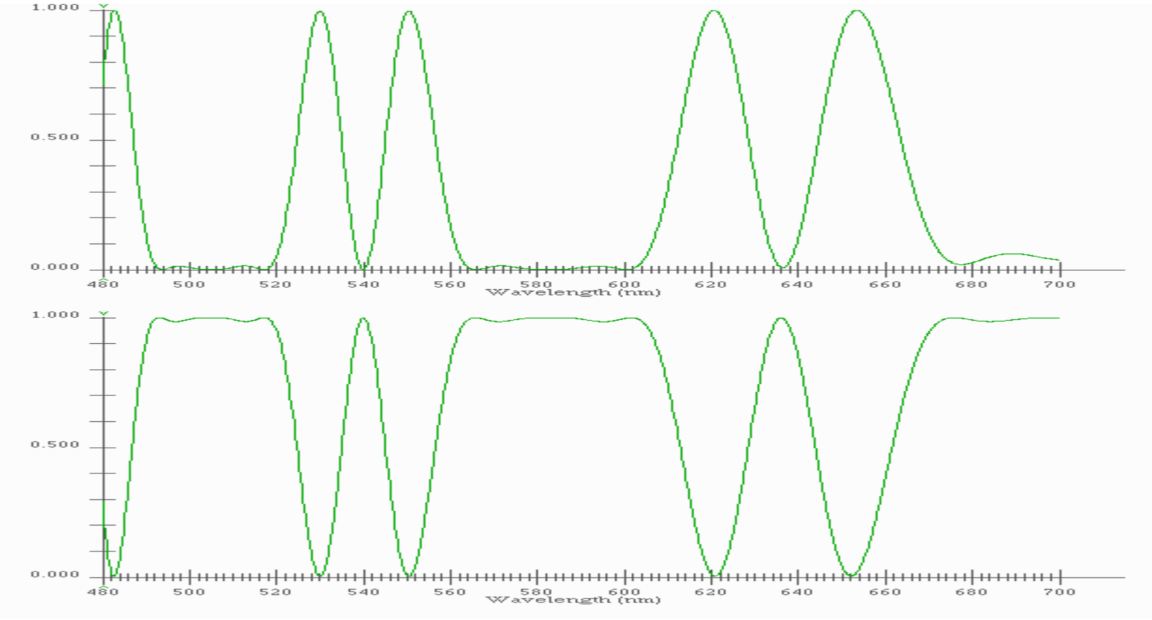

Figure 3 - The two complementary spectra of a discretely tuned FLC filter.

Continuous Tuning with FLC

The ability to continuously tune a Lyot structure using FLC is not trivial. Limits in the physical capabilities of the FLC materials require innovative designs. However, the enhanced speed of the FLC-based filter designs justify the added complexity.

Figure 3 shows examples of the normalized output spectra measured for a tunable Lyot stage while various voltages were applied to the FLC layer. The spectra were obtained using an optical spectrum analyzer. The first transmission spectrum consists of two nulls. With –10V applied to the analog FLC retarder, one null is in the green, the other at the long end of the red. Each of these nulls blue-shifts with increased voltage, that is, the green null shifts to blue and the red null shifts to green. The filter tunes through one period in the green.

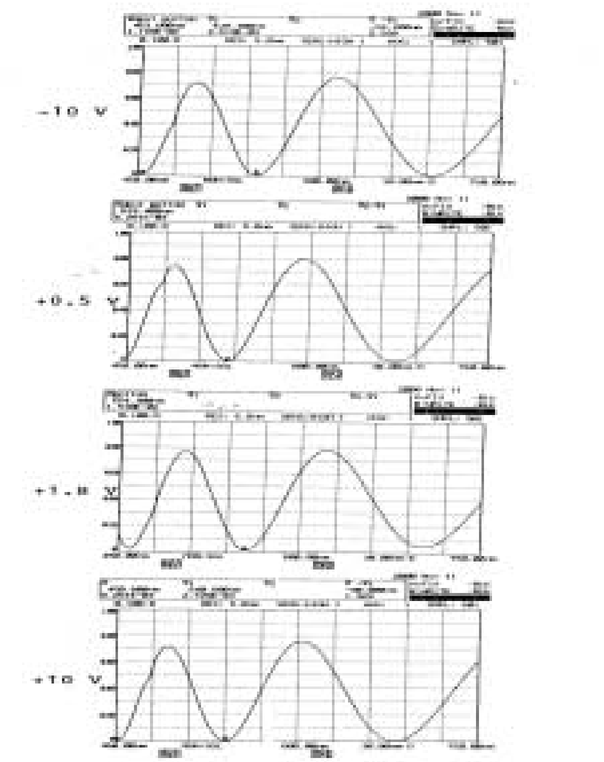

Figure 3 - Experimental spectra for various voltages applied to an FLC-based single stage Lyot filter.

Table 1 gives the voltage dependence of the two null wavelengths. Measurement error is ± 2 nm.

Applied Voltage	Green to Blue Null Shift	Red to Green Null Shift
-10 V	548 nm	695 nm
0 V	537 nm	676 nm
0.5 V	533 nm	670 nm
1.0 V	529 nm	665 nm
1.5 V	513 nm	630 nm
1.8 V	461 nm	554 nm
3.0 V	454 nm	549 nm
10 V	450 nm	540 nm

Table 1 - Null shift as a function of voltage for the single stage tunable Lyot filter implemented using analog switching FLC.

Considerations When Using FLC-Based Lyot Filters

An ideal Lyot structure is very useful for its arbitrary resolution and imaging capabilities. In practice, however, transmission efficiency degrades rapidly with increased number of stages, due to the number of polarizers needed. The speed of FLC may very well compensate for the loss in transmission efficiency when total light throughput is considered. Because of the number of active devices involved, the filter thickness can become bulky, and electronic driver requirement complex with added stages.

Table 2 below demonstrates how the filter characteristics change with the number of filter stages. The filter below was centered at 600 nm, for operation in the 400-700 nm operating range. The resolution of the filter is the width of the passband measured at the half-power point when tuned to 600 nm. The transmission efficiency assumes linear input light. The highest sidelobe level is determined by the peak transmission of the highest out-of-passband point.

Number of Stages	Resolution (nm)	Tuning Range	Transmission Efficiency	Highest Sidelobe	Device Thickness (mm)
1	209	400 nm - 600nm	64 %	8 %	8
2	133	414 nm – 600nm	48 %	4 %	16
3	63	492 nm – 600nm	36 %	3 %	24
4	31	541 nm – 600 nm	28 %	2 %	32
5	16	569 nm – 600 nm	20 %	2 %	40
6	8	584 nm – 600 nm	12 %	1.5 %	48

Table 2 – Filter Characteristics with number of filter stages.

In summary, there are two distinct types of FLC-based polarization filters: discrete and continous. Discretely tuned FLC-PIFs produce two complementary spectra. Multiple stages can be stacked to produce multiple passbands, but at the expense of transmission efficiency and complexity. Continously tuned filters are best suited to low resolution applications. Higher resolution devices require so many stages, (resulting in loss and increased device thickness) as to be considered impractical.